Changes in Kinematics and Arm-leg Coordination during a 100 m Breaststroke Swim.

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Abstract

The purpose of this study was to compare arm-leg coordination and kinematics during 100 m breaststroke in 26 (8 female; 18 male) specialist breaststroke swimmers. Laps were recorded using three 50Hz underwater cameras. Heart rate and blood lactate were measured pre and post swim. Arm-leg coordination was defined using coordination phases describing continuity between recovery and propulsive phases of upper and lower limbs: CPhase1, (time between end of leg kick and start of the arm pull phases); and CPhase 2, (time between end of arm pull and start of leg kick phases). Duration of stroke phases, coordination phases, swim velocity, stroke length, stroke rate, and stroke index were analysed during the last three strokes of each lap that were unaffected by turning or finishing. Significant changes in velocity, stroke index and stroke length ($p < 0.05$) were found between laps. Both sexes showed significant increase ($p < 0.05$) in heart rate and blood lactate pre to post swim. Males had significantly ($p < 0.01$) faster swim velocities resulting from longer stroke lengths ($p = .016$) with no difference in stroke rate ($p = .064$). Sex differences in kinematic parameters can be explained by anthropometric differences providing males with increased propelling efficiency.

Keywords

Arm-leg coordination, Kinematic Analysis, Breaststroke, Swimming, Sex differences.

Introduction

Breaststroke swimming is inherently an in-phase rhythmical movement that involves stable and flexible modes of coordination between the upper and lower limbs. These movements arise as a result of the interactions between the mechanical properties of the water and the intrinsic dynamics of the body (Seifert, Chollet, & Bardy, 2004).

Male breaststroke swimmers have higher linear velocities, than females, resulting from longer stroke length (SL) and higher stroke rate (SR) (Seifert & Chollet, 2005). The differences between sexes in the combinations of SR and SL and arm-leg coordination may be partly explained by anthropometric differences, the swimmer's technique, and the resultant active drag, velocity and ratio of SL and SR (Kolmogorov & Duplischeva, 1992). Therefore, differences in the ratio of SR and SL may also be related to variation in the stroke phases, arm and leg recovery, propulsive phases and glide phase (Chollet, et al., 1996; Chollet, et al., 1999; Soares, et al., 1999; Seifert & Chollet, 2005).

Male and female swimmers organise their arms and legs differently throughout 50-200 m swims (Seifert & Chollet, 2005). There is currently no information on whether the sexes make similar changes in the phasing of the arms and legs as they progress through a race. As pace increases from 200 to 50 m there is an increase in the propulsive phase and a reduction in the glide phases of the stroke cycle in males and females (Seifert & Chollet, 2005). The spatio-temporal differences between the sexes may be due to anthropometric differences and different stroke phase durations linked to arm – leg coordination (Seifert & Chollet, 2005). It has previously been shown that a difference in anthropometry between the sexes mediates differences in SL, SR and swim velocity in front crawl swimming (Chatard, et al., 1991; Grimston & Hay, 1986). Male swimmers have been reported to have greater stature and longer segment lengths, linked to higher propelling efficiency and longer SL's in front crawl swimming (Kjendlie, Stallman, & Stray-Gundersen, 2004). This has not been investigated in breaststroke swimmers. Stroke index (SI) as defined by Costill, et al. (1985) is the product of average velocity (v) and SL and is considered a valid indicator of swimming efficiency. Female swimmers are reported to be more efficient than their male counter parts in breaststroke swimming due to the elevated position they adopt in the water (McLean & Hinrichs, 1998). What is unclear is how SI changes during a breaststroke swim and whether it differs between sexes. It is also important to recognise that multiple factors contribute to swimming performance with biomechanical, anthropometric and physiological (oxygen uptake, blood lactate) responses being identified as key contributors to swimming performance (Lätt et al., 2010). Thus in the context of neuromuscular fatigue, over the course of a timed swim, assessment of mechanical, anthropometric and physiological variables is needed. In addition, assessment of muscle activity responses during swimming, alongside SI and SL, can help us understand if and how motor control reorganisation might assist in maintaining swim speed (Conceicao et al., 2014).

Previous studies that have examined arm-leg coordination in breaststroke swimming (Chollet, Seifert, Leblanc, Boulesreix, & Carter, 2004; Leblanc, Seifert, Baudry, & Chollet, 2005; Leblanc, Seifert, & Chollet, 2005, 2009; Seifert & Chollet, 2005, 2009), have used discontinuous graded protocols of 25 m. Arm-leg coordination has been determined (Chollet, et al. 1999; Leblanc et al. 2005; Seifert & Chollet, 2005) via measurement of time gaps between the different phases of the upper and lower limbs. The investigation of coordination changes during a race could provide a better understanding of a swimmer's personal coordination style, and how modifications in coordination relate to SL, SR and swim velocity. Such investigation would provide enhanced understanding of swimming performance. This could inform the design of interventions (Pelayo, Alberty, Sidney, Potdevin, & Dekerle, 2007) to maximise performance. The aims of this study were to: (1) compare arm-leg coordination between each lap of a 100 m swim and relate this to changes in swim velocity, SL, SR and SI; (2) Compare arm-leg coordination, swim velocity, SL, SR and SI between sexes; It was hypothesised that: (1) there will be a decrease in clean swim speed from the 1st to the 4th lap with an associated decrease in SL and SR and there will be a change in the coordination of the arms and legs from the 1st to the 4th lap; (2) males will have higher swim velocities and longer SL than females due to anthropometry differences and there will be a difference in the coordination of the arms and legs between sexes; (4).

Materials and Methods

Participants

Following institutional ethics approval, informed consent and parental informed consent, n=26 competitive specialist breaststroke swimmers (18 males FINA points mean ± SD 618 and 8 females, FINA points mean ± SD 804 ± 118 based on FINA points scoring 2015 for 100 m short course.) (Table 1.0) participated in this study. The swimmers were currently competing at national level and were part of an Amateur Swimming Association beacon squad. This squad sits below competitive adult international standard and forms the focus for talent development in UK swimming.

Anthropometric Measurements

Height (m) and mass (kg) were assessed using a SECA stadiometre and weighing scales

(SECA Instruments Ltd, Hamburg, Germany). Limb lengths (Table 1.0) were assessed using a non-stretchable tape measure in accordance with the International Society for the Advancement of Kinanthropometry (Lindsey Carter & Ackland, 1994).

Physiological Measurements

Heart rate was measured following 15 minutes of seated rest (Polar, Finland) and 25µl of capillary blood was taken from an earlobe and analysed using a Lactate Pro analyser (Arkray, Japan) in accordance with BASES Guidelines (1997) pre swim. Heart rate was taken immediately post 100 m swim and blood lactate concentration was sampled 5 minutes post (Goodwin et al. 2007).

Ratings of perceived exertion (RPE) using the 6-20 Borg Scales (Borg, 1998) were recorded immediately post 100 m swim.

Swim Trials

A self-selected 800 m warm-up in a 25 m pool (Thompson, MacLaren, Lees, & Atkinson, 2003) was completed prior to completing a maximal 100 m swim from a water start with no pre conceived pacing strategies. The skin overlaying the joint centres (lateral malleolus, lateral femoral condyle, greater femoral trochanter, styloid process, epicondyle of humerus and acromion process) were marked on both sides of the body using black PVC electrical tape (19 mm). Both sides of the body were marked as the right side was used for qualitative analysis (Dartfish Trainer 2.5.2., Switzerland) on laps 1 and 3 and the left side on laps 2 and 4.

Cameras 1 and 2 (Sony DCR-TRV460E), sampling at 50Hz, were enclosed in a custom made waterproof housing at each end of the lane (Fig 1.0). Camera 3 sampling at 50Hz was a waterproof bullet camera, which was suspended underwater (0.4 m) from the trolley and connected to a Sony GV-D800E visual display unit located on the trolley. The field of view of each camera was adjusted so that the whole body of each participant was visible. The frontal and rear camera views were synchronised to the sagittal view (Dartfish Trainer 2.5.2., Switzerland) using a custom made LED light trigger system. The trolley was manually moved parallel to the greater femoral trochanter throughout the entire 100 m swim.

< Insert Fig 1.0>

Figure 1. Plan view of the filming set-up used for qualitative analysis

Time to complete 100 m was recorded (to the nearest 0.02s) (Dartfish Trainer 2.5.2., Switzerland) as the time from when the feet left the wall at the start until the double hand touch on the wall at the end of the swim.

Stroke Parameters

The following stroke parameters were calculated over a 10 m section identified from the calibration rope, with markers every meter suspended horizontally in the water directly beneath the participant (Fig 1.0). This was done for all four laps and analysed in the video analysis package. The 10 m section (a) was used for the 1st and 3rd lap and section (b) (Fig 1) was used for the 2nd and 4th lap all sections were unaffected by starting, turning or finishing techniques for all four laps from the sagittal plain. *Swim velocity* ($m \cdot s^{-1}$) was defined as the mean forward velocity of the greater trochanter, to the nearest 0.01 $m \cdot s^{-1}$, from the time when the greater trochanter entered to when it left the 10 m testing section (Fig 1.0); *Stroke frequency* ($stroke \cdot min^{-1}$) was defined as the number of stroke cycles performed in one minute, to the nearest 0.01 $strokes \cdot min^{-1}$, calculated as the mean over each of the 10 m testing sections (Fig 1.0) ; *Stroke length* ($m \cdot cycle^{-1}$) was defined as the distance that the participant's greater trochanter travelled in one stroke cycle, to the nearest 0.01m, computed from the swim velocity and the SR values); *Stroke Cycle Time* (s) was defined as the time taken to complete one complete stroke cycle, calculated as the mean stroke cycle time over the 10 m testing sections (to the nearest 0.02 s); Stroke index (SI) (Costill et al., 1985).

Arm and Leg Coordination and Stroke Phases

Three complete stroke cycles (Chollet et al., 2004), completed within the 10 m testing section on each lap, were analysed using the synchronised frontal and sagittal video (Fig 1.0) to determine the average duration of each of the following phases: Arm Pull (time between separation of the hands from the extended position in front of the body until first forward movement of the elbow when the hands were under the head); Arm recovery (time between the end of the arm pull phase and start of the separation of the hands from the extended position); Leg kick (time between the start of the first backwards movement of the feet, the point where the legs were maximally flexed at the start, and the point when the legs were fully extended); Leg recovery (time between the end of the leg kick phase and complete flexion of the knee until forward movement of the feet had finished); Coordination phase 1 (CPhase1) was calculated as time between the end of the leg kick phase and start of the arm recovery phase and was used to classify the participants coordination as overlap (represented by a negative value to the nearest 0.02 s indicating simultaneous propulsion of the upper and lower limbs), glide (represented by a positive value to the nearest 0.02 s indicating a delay (glide) in the initiation of the arm pull phase) or continuous; Coordination phase 2 (CPhase 2; time between the end of the arm pull phase and the start of leg kick phase); Arm lag time (ALT; corresponded to time from the start of the leg kick to the beginning of arm pull). All phases were expressed as a percentage of total cycle time with a precision of 0.02 s (Fig 2). It should be noted that the start of the arm pull phase and the end of the arm pull phase, as described above, does not necessarily correspond the start and end of the propulsive components of the arms' stroke, similarly for the leg kick, the start of the leg kick and the end of the leg kick does not necessarily correspond to the start and end of the leg propulsion (Maglischo, 2003). The key stroke phases of the upper and lower limbs were subjectively determined by three independent operators using a blind technique. The three independent analyses were then compared with the mean difference of the operators being (< 0.04 to the nearest 0.02 s), which was less than the 0.04 s which has previously been used to validate key stroke phases (Seifert, Chollet, & Chatard, 2007).

< Insert Fig 2>

Figure 2. Definition of stroke phase and measurement of arm-leg coordination in breaststroke swimming. The block diagram describes the phases of the stroke with time increasing along the horizontal axis. A negative CPhase 1 is shown in the block diagram representing overlap coordination.

Statistical Procedures

Statistical analyses were conducted using SPSS v16 (SPSS, Inc., Chicago, IL, USA). Mean and standard deviation were calculated for all measured variables. Independent T tests were used to determine sex differences within the anthropometry data. The effect size of the independent T test was estimated using Pearson's correlation coefficient in accordance with Rosnow & Rosenthal (2005), values interpreted according to Cohen (1988) as r = 0.10 (small effect), r =0.30 (medium effect) and r = 0.50 (large effect). Two-way Analysis of Variance was used to compare selected kinematic variables at the same point of each of the four laps, with lap (1, 2, 3 and 4) and Sex (males and female) as the fixed factors. Where differences were noted in ANOVA, pairwise comparisons (Bonferroni adjusted) were employed to identify where the significant differences occurred. Effect size for the ANOVA statistics was estimated using partial Eta squared (ηp^2) for analysis of variance according Ferguson (2009). Pearson product moment correlation coefficients were used to determine whether variation in SL or SR was related to variation among selected kinematic variables for each lap. An alpha level of 0.05 was set a priori.

Results

Anthropometric and Physiological Data

<Insert Table 1>

Table 1. Anthropometric measures and performance time of the participants n=26. All values are given as mean ±SD.

Regarding anthropometry (Table 1), there was a significant difference between sexes for height t (24) = 3.13., p =.005, r = 0.56, arm span t (24) = 2.52, p =.02, r = 0.46, forearm length t (24) = 2.23, p =.035, r = 0.41 and hand length t (24) = 2.11, p = .045, r = 0.40. There was a significant increase in both HR (134%) F(1,24) =271, p < 0.001, ηp^2 0.92 (Table 2) and blood lactate concentrations (526%) $F(1,24) = 125$, $p < 0.001$, ηp^2 .839 from before the swim to 5 minutes post the 100 m swim.

<Insert Table 2>

Table 2 Physiological measures at rest and post 100 m swim of the participants n=26. All values are given as mean ±SD.

Performance Data

Analysis of variance of swim velocity showed a significant main effect for sex $F(1,24) = 5048$, $p < .001$, ηp^2 0.89 (Table 3). Over the four laps males had significantly higher (8%) swim velocity than females (1.17 $m \cdot s^{-1}$ ± 0.05 vs. 1.06 $m \cdot s^{-1}$ ± 1.05). There was a significant main effect for lap $F(3,72) = 37.31$, $p < .001$, ηp^2 0.61. Post hoc comparisons indicating a significant decrease in swim velocity from the 1st to 2nd ($p = .006$), 2nd to 3rd laps ($p < .001$) with an overall significant ($p < .001$) decrease in swim velocity of 9% from the 1st to the 4th Lap. Males showed a significant decrease in swim velocity from 1st to the 3rd lap ($p = 0.001$) and from the 1st to the 4th lap ($p = 0.003$). The decrease in swim velocity in females followed a similar trend as the males with the decreases approaching statistical significance ($p = 0.053$).

For SL there was a significant main effect for sex $F(1,24) = 6.711$, $p = .016$, ηp^2 0.22 (Table 3) with the males having a 15% longer SL (1.59 $m \cdot cycle^{-1}$ ± 0.24 vs. ± 1.35 $m \cdot cycle^{-1}$ ± 0.24). There was a significant main effect for lap $F(2.6,62.4) = 4.79$, $p = .007$, ηp^2 0.17 with post hoc comparisons showing a significant decrease only between the 2nd and 4th lap of the swim. The mean SL over the four laps showed significant correlation with average swim velocity ($r = .540$, $p < 0.01$). The mean SL over the four laps also showed significant correlation with forearm length ($r = .397$, $p < 0.05$) and a significant negative correlation with arm span ($r = .-454$, $p < 0.05$).

For SR there was a significant main effect for lap $F(3,72) = 4.14$, p =.009, ηp^2 0.15 with post hoc comparisons indicating a significant decrease in SR from the 1st to 2nd lap (p = .016) and from the 1st to 3rd lap (p = .044).

For SI there was a significant main effect for sex $F(1,24) = 618.7$, p =.003, ηp^2 0.31 (Table 3) with males on average having a 31% higher SI than females (1.88 $m^2 \cdot s^{-1}$ ± 0.32 vs. 1.43 $m^2 \cdot s^{-1}$ ± 0.28. There was a significant main effect for lap $F(2.1,49.3) = 14.4$, $p < .001$,ηp^2 0.38 with post hoc comparisons showing a significant decrease in SI from the 1st to 3rd (p =.012) and 1st to 4th lap ($p < 0.001$).

<Insert Table 3>

Table 3 Mean ± SD values and coefficient of variation percentage (CV%) for swim velocity, stroke length (SL), stroke rate (SR), stroke cycle time and stroke index (SI) for males (n=18) and females (n=8) over the four laps of the 100 m swim

Arm-Leg Coordination

The analysis of CPhase 1 showed that nine participants (females n=4 and males n=5) utilised the overlap coordination technique (CPhase1 -13.4% ± 1.9), thirteen participants (females n=3 and males n=10) utilised glide coordination technique CPhase1 11.9% ± 1.0) and four participants (female n=1 and males n=3) started with the glide coordination technique but changed to the overlap coordination between the 1st and the 4th lap (CPhase 1 -0.3% ± 4.8). Of the four participants that changed from the glide to the overlap coordination technique, three participants (female n=1 and males n=2) altered their coordination on the final lap and the other participant changed their coordination technique on the 2nd lap.

<Insert Table 4>

Table 4 Mean ± SD values and coefficient of variation percentage (CV%) of arm and leg stroke phases and arm-leg coordination expressed as a percentage for males (n=18) and females (n=8) over the four laps of the 100 m swim. CV was not calculated for CPhase1 due to the existence of both positive and negative values.

Discussion

Comparison between laps

The current study indicates that swim velocity decreased over the duration of the 100 m swim with a drop off in velocity of 8 and 9% for 3rd and 4th laps respectively, similar to the 7% reported by Thompson, et al. (2000) from the 1st to 2nd lap of a 100 m long course breaststroke swim. The decrease in swim velocity was related to the change in the ratio of SL and SR as there was a significant decrease in SR from the 1st to the 2nd and 3rd laps of the swim with an increase seen on the final lap as there was no significant difference to the 1st lap. There was no significant change in SL over the duration of the swim. This is in contrast to Thompson, et al. (2000) that reported a significant decrease of 9.7% in SL. The decrease in swim velocity, in the present study, coincided with a significant decrease (13%) in SI which indicates that the participants were becoming less efficient as they progressed through the swim.

The change in swim velocity over the duration of a breaststroke swim has been suggested to occur as a result of the onset of fatigue in the leg muscles due to the heavy reliance on the legs for propulsion in breaststroke swimming (Maglischo, 2003), resulting in metabolic acidosis (Thompson, 1998). Fatigue denotes a transient decrease in the capacity to perform physical activity (Enoka & Duchateau, 2008), as shown by the decrease in swim velocity. This could be due to local muscle fatigue connected to metabolic acidosis as shown by raised levels of blood lactate after the 100 m swim (Table 1.0). There could also be an unmeasured component of central fatigue in the present study, leading to an inhibition of the working muscles as a result of afferent feedback from the muscles, joints and tendons inhibiting motor activity at the spinal or supraspinal levels contributing to the observed loss of swimming performance (James, Sacco, & Jones, 1995). The decrease in SI due to fatigue mechanism could lead the participants to utilise compensatory mechanisms to try and maintain swim velocity. It has been previously reported that compensatory mechanisms (Forester & Nougier, 1998) of fatigue are such that other muscles take over the function of the muscles that normally perform the repetitive task, thus resulting in greater variability in the participants techniques. Further studies are needed to investigate the compensatory mechanisms and see how changes in muscle activation affect the efficiency of swimmers. This is speculative but supported by decreases in SI over the duration of the swim.

In the current study, the most commonly used arm-leg coordination pattern on 1st lap was the glide technique (65% of swimmers). The remainder utilised the overlap pattern. As the participants progressed from the 1st to the 4th lap, 96% of the participants altered their arm-leg coordination pattern. Of these, 68% moved closer towards the overlap technique or increased the amount of overlap in their technique. The overlap technique (Seifert & Chollet, 2005) is characterised by an overlap of the propulsive phases of the upper and lower limbs and. reduces velocity fluctuations making the stroke more economical (Vilas-Boas, 1996). These participants could have inverted their coordination strategy to move away from the lower limbs placing greater reliance on the upper limbs for propulsion resulting in the reduced glide phase. Further investigations are required to investigate the shift from the lower limbs to the upper limbs for propulsion during breaststroke swimming. The remaining participants showed an increase in the amount of glide or a decrease in the overlap in their technique from the 1st to 4th lap. It is postulated that participants altered the timings of the stroke as a result of fatigue, which hampers the sensorimotor system (Forestier & Nougier, 1998; Tripp, Yochem, & Timothy, 2007), thus altering functions of awareness, feedback and coordination causing an inability to maintain ideal mechanics, resulting in changes to the neuromuscular system in an attempt to maintain homeostasis which is evidence of increasing variability. However, further investigations to substantiate this line of enquiry are required.

In the present study the inter-lap comparisons show that the participants showed no change in the amount of time spent in the propulsive phases of the stroke or the recovery phases of the stroke. The fact there is no change in time spent in the propulsive phases of the stroke can explain why there was no change in SL over the duration of the swim. However this does not explain why there was a decrease in SI over the duration of the swim. Further investigation is needed to understand the decrease in SI and the overall decrease in swim velocity. Similar results were reported for the coordination phases (CPhase 1 and CPhase 2). The findings of the current study cannot be directly related to other breaststroke studies as to the authors knowledge this is the first study that has investigated changes in coordination during a 100 m swim in breaststroke. All the previous studies that have investigated the changes in arm-leg coordination during a swim have all investigated changes in front crawl swims (Alberty, Sidney, Huot-Marchand, Hespel, & Pelayo, 2005; Seifert, Chollet, & Chatard, 2007; Toussaint, Carol, Kranenborg, & truijens, 2006). Alberty et al. (2005) reported a decrease in the non-propulsive phase with a corresponding increase in the propulsive phases in the front crawl stroke. The increased time spent in the propulsive phase of the stroke on the 4th lap of a 100 m swim may be as a direct result of a slower hand velocity which, has been linked to a slower swimming velocity (Toussaint et al. 1988) and a decrease in SL. In the current study there was no increase in the time spent in the propulsive phase of the stroke cycle for either the upper and lower limbs. In breaststroke there is a glide phase for the upper and lower limbs which may be adequate to allow sufficient recovery, thus maintaining hand velocity.

Comparison between sexes

In regard to sex effects, males had significantly (by 8%, Table 3) higher swim velocities than females over the four laps, which is consistent with previous studies (Seifert & Chollet, 2005; Takagi et al., 2004). As swim velocity is a product of SL and SR, and SR was similar in both sexes, this is likely explained by the 15% longer SL identified in males (Table 3), which is consistent with previous studies (Thompson, et al. 2000; Takagi, et al. 2004). Longer SL in males can be attributed to the fact that males were significantly taller (4.7%) and presented significantly longer segment lengths for hand (5.6%) and forearm (8%) (Table 3.0). The longer segment lengths and greater stature have been strongly correlated to SL in front crawl swimming (Chatard et al., 1991). The lower propelling efficiency of the females could be due to lower active drag values, which have been reported in front crawl swimming (D = 24 v^2 vs. D = 30 v^2) (Toussaint et al., 1988). The previously reported lower cross-sectional area (0.0075 m^2 *vs.* 0.091 m^2) of females along with smaller hand and foot lengths produces lower active drag at comparable velocities (Toussaint et al., 1988). Male swimmers have also been reported to generate greater mechanical power outputs (P_d) than females (Kolmogorov, Rumyantseva, Gordon, & Cappaert 1997). The greater segment lengths of males provides a superior propelling surface to generate propulsive forces which constitutes a performance advantage in competitive swimming (Toussaint, Janssen, & Kluft, 1991; Kjendlie, et al., 2004) as propelling efficiency has been shown to increase SL (Troup, 1999; Toussaint, Van Den Berg, & Beek, 2002).

In the current study females adopted a motor coordination pattern that was characterised with a negative CPhase 1 over all four laps of the swim compared to males that started with a glide coordination technique that altered towards the overlap technique from the 1st to 4th lap. This is different to previous findings of Seifert & Chollet, (2005) who reported that males had significantly shorter glide times compared to females. The differences in findings between that of Seifert & Chollet, (2005) study could be due to the fact that they used national finalist or internationally ranked swimmers compared to elite club swimmers used in the current study. In the current study there was no significant difference between sexes in the time spent in any of the phases of the stroke which again is not consistent with Seifert & Chollet, (2005) who reported that males spend significantly longer in the propulsive phase of the stroke. In these previous studies authors have measured changes in arm-leg coordination of the stroke using pre-determined velocities representative of 50, 100 and 200 m over a single length. In the current study there was no difference between sexes regards the time spent in the phases of the stroke. This is in contrast to Takagi, et al., (2004) who reported sex differences in simultaneous propulsion which in the current study was identified with coordination phase 1 (CPhase1). The reason for the difference could have been the level of the swimmers used in the study or more likely that in the current study CPhase 1 was investigated over each of the four laps compared to Takagi, et al., (2004) who only investgated coordination on the 1st lap when the swimmers were fresh. This may have been due to the fact that this was a 100 m swim and the significant changes are greater between males and females in the 50 m sprint competitions.

Conclusion

This study has investigated changes in stroke kinematics over the duration of a 100 m breaststroke swim in both males and females. Intra lap comparisons showed that there was a significant decrease in swim velocity over the duration of the swim with similar changes in both sexes. These inter lap changes can be explained by the accumulation of fatigue throughout the swim which reduced the stroke efficiency of both sexes with a significant decrease in inter lap SI. A similar decrease was shown for SR over the 1st to the 3rd lap of the swim which explains the decrease in swim velocity. Even though there was a significant decrease in swim velocity there were no significant changes in the time spent in each of the stroke phases.

Practical applications.

The current study has demonstrated that coordination changes occur during a 100 m short course swim. Therefore, when analysing technique both individual arm-leg coordination strategies and sex differences need to be considered. This is important for coaches and sports scientists to consider when analysing swimmers technique. A better understanding of individual changes can assist in the planning and implementation of training interventions. However further investigations are required to substantiate these findings and understand the reduction in efficiency.

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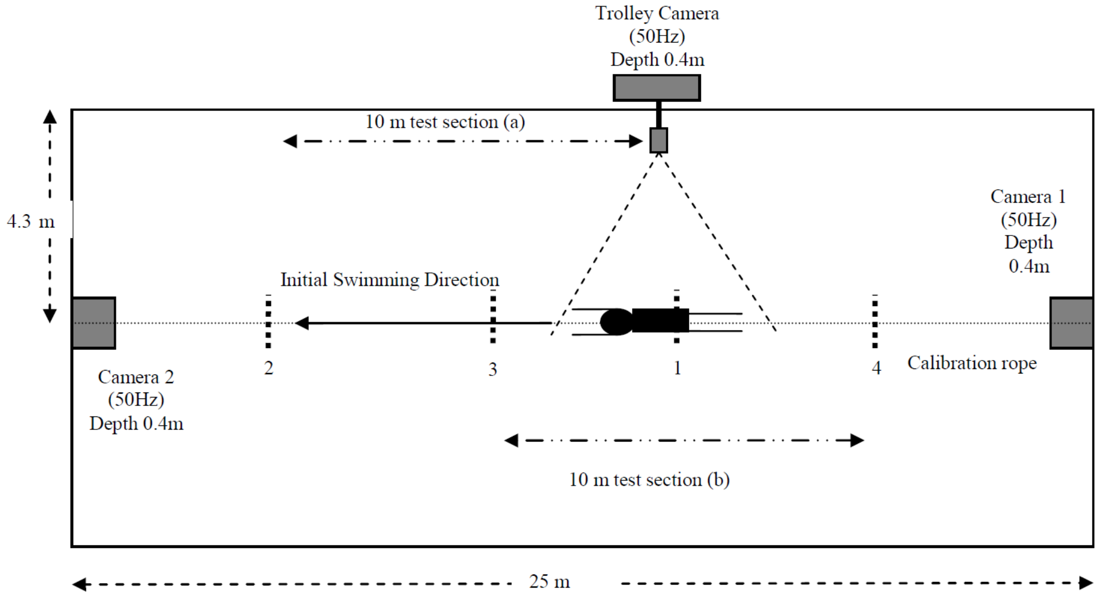

Figure 1. Plan view of the filming set-up used for qualitative analysis

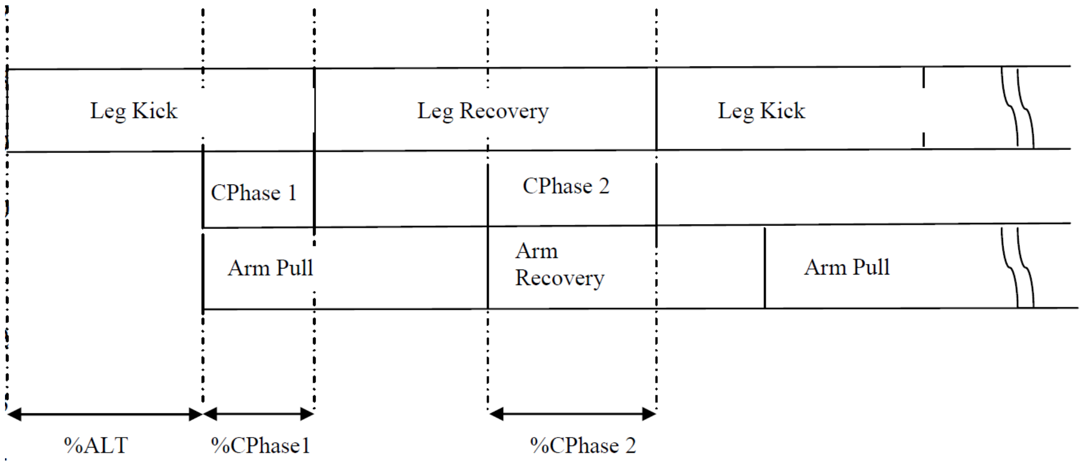

Figure 2. Definition of stroke phase and measurement of arm-leg coordination in breaststroke swimming. The block diagram describes the phases of the stroke with time increasing along the horizontal axis. A negative CPhase 1 is shown in the block diagram representing overlap coordination.

Table 1 Anthropometric measures and performance time of the participants n=26. All values are given as mean ±SD.

Participant	Age (years)	Height (m)	Body mass (kg)	Arm Span (m)	Upper Limb Length (m)	Forearm Length (m)	Hand Length (m)	Performance Time 100m (s)
Female (n=8)	19.1±2.3	1.70±0.05*	69.0±8.0	1.73±0.07*	0.33±0.02	0.24±0.02*	0.19±0.01*	88.3±5.4*
Male (n=18)	18.9±2.2	1.78±0.06	69.3±7.3	1.83±0.10	0.34±0.03	0.26±0.02	0.20±0.01	77.5±5.5

*Denotes statistically significant difference $p < 0.05$ between sexes

Table 2 Physiological measures at rest and post 100 m swim of the participants n=26. All values are given as mean ±SD.

Participant	Resting Heart Rate (Beats·min^{-1})	Post Swim Heart Rate (Beats·min^{-1})	Resting Blood lactate (mmol·L^{-1})	Post Swim Blood Lactate (mmol·L^{-1})	Post Swim RPE
Female (n=8)	79±11#	183±10#	1.0±0.3#	6.6± .2#	18±1
Male (n=18)	75±17	173±30	1.3±0.4	8.0±2.8	17±1

# Denotes statistically significant difference $p < 0.05$ sexes

Table 3 Mean ± SD values and coefficient of variation percentage (CV%) for swim velocity, stroke length (SL), stroke rate (SR), stroke cycle time and stroke index (SI) for males (n=18) and females (n=8) over the four laps of the 100 m swim

	1st Lap	2nd Lap	3rd Lap	4th Lap
Swim Velocity ($m \cdot s^{-1}$)				
Male[a]	1.24±0.10 (cv=8)	1.19±0.07 (cv =6.2)	1.13±0.07 (cv=6.5)	1.14±0.08 (cv=7)
Female	1.11±0.06 (cv=5.5)	1.07±0.08 (cv=7.5)	1.04±0.08 (cv=7.5)	1.00±0.08 (cv=7.9)
Group Mean	**1.20±0.11**	**1.15±0.09**[b]	**1.10±0.08**[c,e]	**1.10±0.10**[d]
SL ($m \cdot cycle^{-1}$)				
Male[a]	1.62±0.24 (cv=15)	1.64±0.22 (cv=13.7)	1.57±0.22 (cv=13.9)	1.55±0.24 (cv=15.4)
Female	1.39±0.24 (cv=17)	1.39±0.24 (cv=17)	1.36±0.27 (cv=19.7)	1.28±0.22 (cv=17.1)
Group Mean	**1.55±0.26**	**1.56±0.25**	**1.50±0.25**	**1.47±0.26**
SR ($stroke \cdot min^{-1}$)				
Male	46.8±7.4 (cv=15.8)	44.3±6.5(cv=14.7)	43.7±5.6 (cv=12.7)	44.8±6.0 (cv=13.4)
Female	49.7±8.2 (cv=16.6)	47.2±6.8 (cv=14.4)	47.2±8.4 (cv=17.7)	47.3±7.7 (cv=16.2)
Group Mean	**43.3±6.8**	**41.3±6.4**[b]	**41.2±6.8**[c]	**42.0±6.3**
Stroke Cycle time (s)				
Male	1.45±0.22 (cv=15.3)	1.52±0.22 (cv=14.5)	1.53±0.21 (cv=13.4)	1.49±0.20 (cv=13.2)
Female	1.36±0.26 (cv=18.9)	1.40±0.26 (cv=18.2)	1.40±0.28 (cv=19.9)	1.38±0.25 (cv=18.2)
Group Mean	**1.42±0.23**	**1.48±0.23**	**1.49±0.23**	**1.46±0.22**
Stroke Index ($m^2 \cdot s^{-1}$)				
Male[a]	2.01±0.41 (cv=20.2)	1.95±0.32 (cv=16.3)	1.77±0.32 (cv=17.8)	1.77±0.36 (cv=20.2)
Female[a]	1.54±0.26 (cv=16.9)	1.49±0.32 (cv=21.7)	1.41±0.33 (cv=23.5)	1.29±0.26 (cv=20.4)
Group Mean	**1.87±0.42**	**1.81±0.38**	**1.66±.0.36**[c,e]	**1.62±0.40**[d]

[a] Denotes a statistically significant difference $p < 0.05$ between the sexes.

[b] Denotes a statistically significant difference $p < 0.05$ between the 1st and 2nd lap

[c] Denotes a statistically significant difference $p < 0.05$ between the 1st and 3rd lap

[d] Denotes a statistically significant difference $p < 0.05$ between the 1st and 4th lap

[e] Denotes a statistically significant difference $p < 0.05$ between the 2nd and 3rd lap

[f] Denotes a statistically significant difference $p < 0.05$ between the 2nd and 4th lap

Table 4 Mean ± SD values and coefficient of variation percentage (CV%) of arm and leg stroke phases and arm-leg coordination expressed as a percentage for males (n=18) and females (n=8) over the four laps of the 100 m swim. CV was not calculated for CPhase1 due to the existence of both positive and negative values,

	1st Lap	**2nd Lap**	**3rd Lap**	**4th Lap**
Leg Kick (%)				
Males	21.6±5.4 (cv=23.4)	23.0±6.8 (cv=29.6)	22.9±6.4 (cv=27.9)	24.0±8.3 (cv=34.7)
Females	21.6±7.0 (cv=31.2)	22.0±8.2 (cv=36.4)	21.0±7.5 (cv=34.9)	22.7±8.3 (cv=36.6)
Leg Recovery (%)				
Males	76.8±5.4 (cv=7.1)	77.0±6.8 (cv=8.8)	77.1±6.4 (cv=8.3)	76.0±8.3 (cv=11)
Females	74.6±5.0 (cv=6.7)	73.9±7.6 (cv=10.2)	75.1±6.6 (cv=8.8)	73.1±7.9 (cv=10.7)
Arm Pull (%)				
Males	46.1±8.1 (cv=17.6)	46.0±8.8 (cv=19.1)	45.5±8.4 (cv=18.4)	47.7±8.6 (cv=18.1)
Females	48.1±10.3 (cv=21.3)	48.5±10.4 (cv=21.5)	48.4±9.4(cv=19.4)	47.7±7.8 (cv=16.4)
Arm Recovery (%)				
Males	53.9±8.1 (cv=15)	54±8.8 (cv=16.3)	54.5±8.4 (cv=15.4)	52.3±8.6 (cv=16.5)
Females	51.9±10.3(cv=19.8)	51.5±10.4 (cv=20.3)	51.6±9.4 (cv=18.2)	52.3±7.8 (cv=15)

CPhase 1(%)				
Males	7.3±18.6	5.9±16.9	5.5±16.1	0.6±18
Females	-0.4±13.3	-1.4±13.7	-0.4±12.3	-2.9±15.5
C Phase 2 (%)				
Male	23.4±9.7 (cv=41.4)	25.3±4.7 (cv=18.7)	26.3±5.4 (cv=20.7)	27.7±5.2 (cv=18.7)
Female	27.1±6.5 (cv=24)	26.7±4.8 (cv=26.1)	27.2±4.8 (cv=17.7)	28.3±5.6 (cv=19.9)
ALT (%)				
Male	30.7±14.5 (cv=47.1)	28.9±11.5 (cv=39.6)	28.4±10.9 (cv=38.2)	24.6±11.4 (cv=46.6)
Female	25.3±8.7 (cv=34.3)	24.7±6.6 (cv=26.7)	24.5±6.9 (cv=28.1)	24±8.2 (cv=34.2)